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LARGE SPACE STRUCTURES TESTING

By Dr. Henry Waites and Dr. H. Eugene Worley

Structures and Dynamics Laboratory
Science and Engineering Directorate

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16. ABSTRACT

There is considerable interest in the development of testing concepts and facilities that accurately simulate the "pathologies" believed to exist in future spacecraft. Both the Government and Industry have participated in the development of facilities over the past several years. The purpose of this paper is to present the progress and problems associated with the development of the Large Space Structure Test Facility at the Marshall Space Flight Center. This facility has been in existence for a number of years and its utilization has run the gamut from total in-house involvement, third party contractor testing, to the mutual participation of other Government Agencies in joint endeavors.

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INTRODUCTION

As structures become more complicated, pointing and stability requirements become more stringent, and cost of flight systems becomes more prohibitive, the value of accurate and reliable test/simulations will become significantly more important. The value of test results in performance predictions and analysis has been realized for years in the aerospace engineering field. However, these tests and their attendant results have been used and understood mainly as an engineering tool to facilitate and supplement analysis and simulation tools. We must, in the future, move from this aspect of testing and simulation tools that not only provide accurate and reliable engineering data but also are of sufficient fidelity to enable program managers to make budget and management decisions. That is, the test and test results must be so convincing that even our superiors can understand the results! Quite a challenge.

In order to meet this challenge and also provide valuable engineering data, a comprehensive test facility development program has been undertaken at the NASA's Marshall Space Flight Center in Huntsville, Alabama. NASA, working in conjunction with Control Dynamics Company, has developed and is operating a test facility designed to investigate the performance of state-of-the-art control designs in a real world environment. For a detailed indepth discussion of the history and characteristics of this facility see the reference. We have included some brief descriptions in this report for completeness and convenience of the reader. The purpose of this report is not to present the results of the work of that facility, but rather to present the problems encountered and overcome along the road toward the current operational state.

OVERVIEW OF FACILITY

NASA Marshall Space Flight Center has developed a facility in which dynamic behavior and closed-loop control of Large Space Structures (LSS) can be demonstrated and verified. The main objective of the facility is to assess and verify LSS control system techniques so that on-orbit performance can be evaluated and subsequently ensured. The facility consists of an LSS test article which is connected to a payload mounting system that provides control torque commands. It is attached to a base excitation system which will simulate disturbances most likely to occur for Orbiter and Department of Defense payloads. A control computer contains the calibration software, the reference system, the alignment procedures, the telemetry software, and the control algorithms. The total system is suspended in such a fashion that the LSS test article has the characteristics deemed common to all LSS. The facility can be modified extensively to emulate various spacecraft configurations.

The control system focus for the NASA/MSFC LSS GTF work is to verify and assess the dynamic models and control system methodologies. The LSS dynamics and control verification plan

at MSFC is divided into four interacting areas, which are: (1) dynamic modeling, (2) control law synthesis, (3) verification, and (4) the development of hardware flight systems. Each area interacts wth the others from the initial experiment concept to the development of a hardware flight system.

The NASA/MSFC Ground Test Facility evolution began in 1982. The development and implementation of this facility has been performed by MSFC who has been aided by the LSS GTF systems engineering contractor, Control Dynamics Company. Because of its initial "research and development" nature and the press of more urgent NASA programs, funding for the LSS GTF has been limited. Major elements of the facility have been obtained from other programs and other NASA facilities. This is true, for instance, of the ASTROMAST structure (from JPL, used in the VOYAGER Program), the modified Sperry Advanced Gimbal System (from an earlier MSFC pointing control system program), and the actuators and sensors. Other elements, such as the mirrors used in the Image Motion Compensation Subsystem, were fabricated specifically for the facility.

FACILITY DESCRIPTION

The basic Ground Test Facility at NASA/MSFC is depicted in Figure 1. The test article is shown in its unaltered configuration. The subsequent configurations are structurally augmented versions of this basic form, i.e., cruciform and adaptor, VCOSS-II momentum exchangers, antenna and counter weights, and the Image Motion Compensation (IMC) system. The major components comprising the facility are the augmented Advanced Gimbal System (AGS), COSMEC-I, the Kearfott Attitude Reference System (KARS), Apollo Telescope Mount (ATM) rate gyros, accelerometer packages, the Base Excitation Table (BET), the computer system, and the ASTROMAST test article.

AUGMENTED ADVANCED GIMBAL SYSTEM (AGS)

The AGS is a precision, two-axis gimbal system originally designed by Sperry for high accuracy pointing applications. The AGS gimbals serve the elevation plane. A third gimbal has been added to the system in the azimuth plane. The AGS receives torque commands from the control algorithm implemented on the HP-9020AS via the COSMEC-I data acquisition system. The commands are in the form of analog inputs over the range of ± 10 V. This saturation represents a current limit of 27 A which is built into the AGS servo amplifier as a protective measure. Because the AGS servo amplifier outputs a current which causes an applied torque proportional to the current, the control algorithms used in the COSMEC-I must be designed to produce torque command signals.

The AGS gimbal torquers, with the power supply and servo amplifiers used in the LSS GTF, can generate 37.5 ft-lb of torque over an angular range of approximately ± 30 deg. The azimuth torquer is capable of generating 13.8 ft-lb over an angular range of about ± 5 deg. It can, however, be set manually to allow the ± 5 deg of rotation at any position about the 360 deg of azimuth freedom. This allows the test article to be rotated to any position desired without having to remount it.

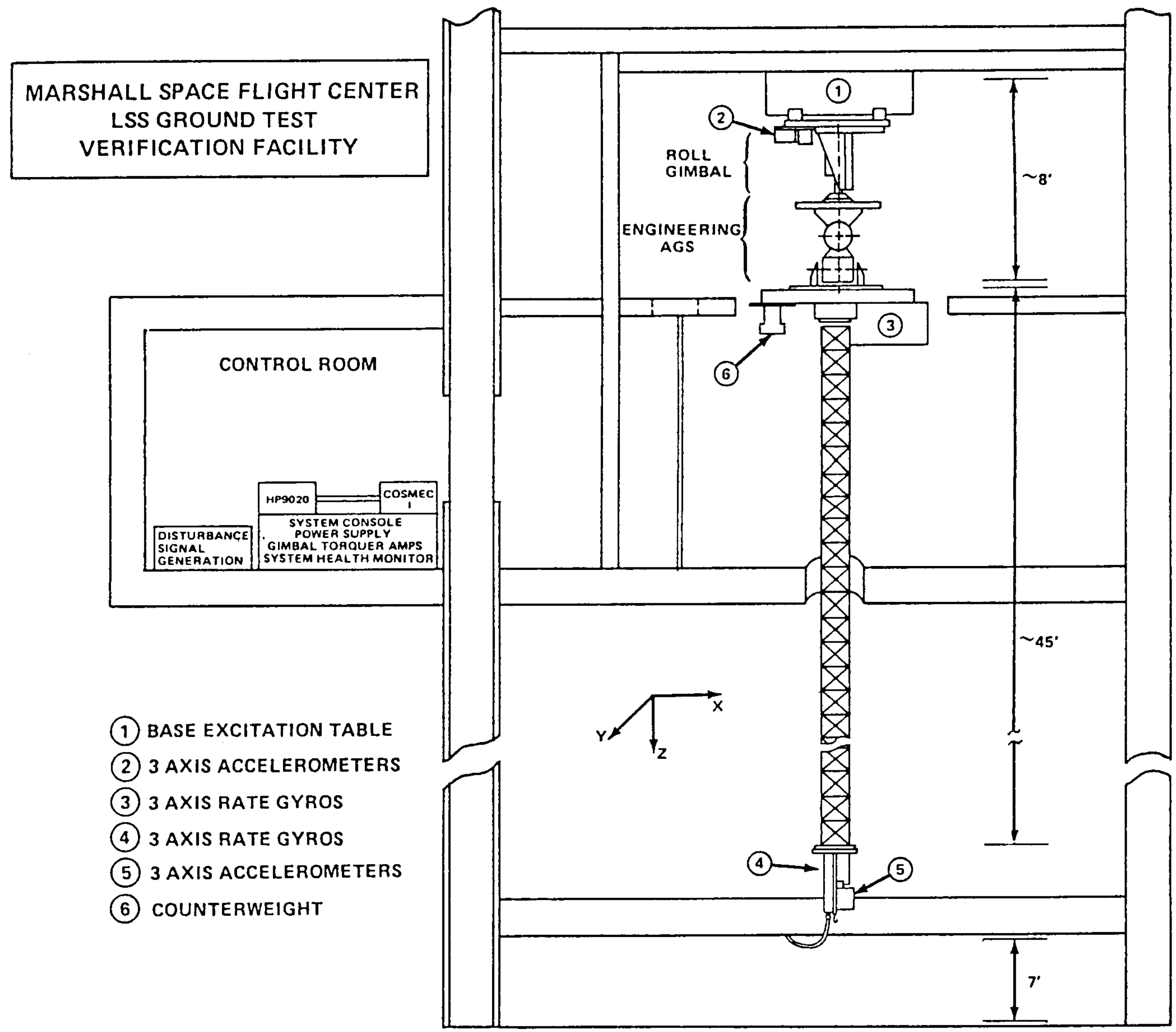

Figure 1. MSFC LSS Ground Test Verification Facility.

COSMEC-I

The primary purposes of the COSMEC-I are to process the sensor inputs, provide torque commands for the AGS, off-load control and sensor data to the computer system, and provide force commands for the LMEDs. Currently the COSMEC-I performs these tasks with 16 sensor inputs, 3 torque outputs, and 4 force outputs, while maintaining a 50 Hz sampling rate. The cycle time for COSMEC operation is approximately 2 msec, while the HP-9020AS uses approximately 10 msec for processing the control algorithm. This provides a margin of 40 percent relative to the 20 msec sampling period.

The COSMEC-I has the capacity to manage 32 differential analog inputs and 32 8-bit digital inputs. The input time per channel is 20 μs for 16-bit parallel digital information and 80 μs for a 12-bit analog data input. The COSMEC-I output capability is 16 analog channels, at ± 10 V, and 32 8-bit digital channels. The output time per channel is 20 μs for 16-bit parallel digital information and 40 μs for 12-bit analog data. The RAM size for the COSMEC-I processor is 32 kbytes and the clock rate is 2 MHz. The COSMEC-I also has an alphanumeric keyboard, a single line display, a cassette tape machine for mass storage, and a small printer.

The COSMEC-I "reads" various types of sensor output signals via interface cards which are an integral part of the COSMEC-I system. These cards allow the COSMEC-I processor to interface in a similar manner (with regard to data format) with the ATM rate gyros, the KARS, the accelerometer packages, the AGS, and the LMED sensors and actuators, each of which has different type input or output signal. The COSMEC-I also features a real time clock which is useful in the recording of experimental data. The hardware cards which interface the COSMEC-I's processor to the measurement instruments and actuators are individual by their very nature, and some special software is required to handle each card. However, each card makes information available to the processor as digital words, which is the unifying feature of the system.

KEARFOTT ATTITUDE REFERENCE SYSTEM (KARS)

The KARS is an attitude measurement system designed for use in the U.S. Army remote pilotless vehicle. It provides measurement resolution of 13.9×10^{-3} deg/sec in the pitch and yaw axes (axes transverse to the ASTROMAST) and 25.0×10^{-3} deg/sec in the roll axis (axis along the length of the ASTROMAST). The dynamic range of the rate gyro outputs of the KARS is 40 deg/sec in pitch and yaw and 70 deg/sec in roll. The KARS is used as the test article mast tip rotation sensor in the facility. Although the KARS includes accelerometers and outputs measurements of linear acceleration, the measurements are not used in the ground test experiments because of inappropriate scaling of the instruments.

The output signals of the KARS are in the form of asynchronous digital pulses which are updated at the rates specified in Table 1. One signal, the change in angular position in yaw for instance, requires two channels: one for pulses representing positive rotation and the other for pulses representing negative rotation. The COSMEC-I system accumulates the pulses over a 20 msec period to produce measurements of the angular rate and position of the ASTROMAST tip.

TABLE 1. KARS OUTPUT UPDATE RATES

Data	Data Rate
Attitude (9 direction cosines)	25 Hz
Velocity (2 components)	4 Hz
Incremental Vertical Velocity	25 Hz
Attitude Rate (3 components)	50 Hz
Body-fixed Acceleration (3 components)	50 Hz

The KARS outputs three digital health check signals. One signal represents a check of the motor voltage and the pickoff excitation voltage and the other two are over and under temperature signals. In the Ground Test Facility these signals will be monitored at the system console.

APOLLO TELESCOPE MOUNT (ATM) GYROS

The ATM rate gyro packages were designed to measure small angular rates precisely. Each package measures angular rates in one axis with resolution finer than 0.5×10^{-3} deg/sec and offers a dynamic range of ± 1.0 deg/sec. The ATM rate gyro packages are mounted on the faceplate of the engineering AGS so that they can measure the rotation of the base of the test article. The output signals of the ATM rate gyro packages are ± 45 V analog and are handled by the analog-to-digital converter card of the COSMEC-I system where they are converted to 12-bit binary words.

ACCELEROMETER PACKAGES

Two identical accelerometer packages are used. One package is placed on the mast tip along with the KARS and the other on the test fixture base. The necessary electronics for each accelerometer package are included onboard the instrument package itself. The accelerometers provide resolution finer than 0.0001 g and a dynamic range of ± 3 g with a bandwidth of 25 to 30 Hz.

The signals from the accelerometers are different from either the KARS or the ATM rate gyros. As in the case of the KARS, two channels are required for each of the degrees of freedom of the accelerometer package, i.e., six channels per accelerometer package. One channel of each pair carries a 2.4 kHz square wave synchronization signal and the other channel carries the acceleration information. Zero acceleration is represented by a signal identical to that of the synchronization channel, positive acceleration by an increase in frequency, and negative acceleration by a signal identical to that of the synchronization channel, positive acceleration by an increase in frequency, and negative acceleration by a decrease in frequency as compared to the synchronization channel. As in the cases of the other instruments, these signals are monitored by a hardware card in the COSMEC-I system.

BASE EXCITATION TABLE (BET)

The BET provides a means of producing disturbance inputs for exciting the system in order to determine the effectiveness of different LSS control methodologies. Currently, the disturbances represent either an astronaut pushoff, a Reaction Control System thruster firing, or a free flyer disturbance. The BET is comprised of a programmable signal generator (deterministic or random noise), DC conditioning amplifiers, hydraulic servo controllers, and an oscillograph. The DC conditioning amplifiers are used to scale the signal generator while the signal conditioners are used to condition the electronic deflection indicator motion monitors for display. The oscillograph is used for recording the actual motion of the BET.

The precise motion of the BET is obtained by supplying a commanded voltage input to the BET servo control system. The BET movements are monitored by the directional feedback electronic deflection indicators which are fed back to the servo controllers. The servo controllers compare the commanded input voltage to the electronic indicators and automatically adjust the position of the BET. The closed-loop controller allows any type of BET movement within the frequency limitations of the hydraulic system.

COMPUTER SYSTEM

The current computer system in use is an HP-9020AS with an HP-IB interface card, two 16-bit parallel interface cards, and 512 kbytes of extra memory. The HP-9020AS is a 32-bit machine with an 18 MHz clock rate. Benchmark test times for processing the distributed sensor control, the disturbance isolation, and the strapdown algorithms are 6 to 10 ms. This, combined with the COSMEC-I and a vector processor, provides sufficient computing power to satisfy the LSS GTF needs for the next few years.

LINEAR MOMENTUM EXCHANGE DEVICES (LMEDs)

The LMED provides a colocated sensor actuator pair with which a force can be applied to a structure in a linear manner and the acceleration at the actuator location be sensed. The LMEDs consist of a linear permanent magnet motor whose magnet functions as a proof mass. Force is applied to the structure as a reaction against this proof mass. The magnet assembly travels along a single shaft on a pair of linear bearings. The coils of the motor consist of a hollow voice coil which extends inside the magnet assembly from one end. The magnet assembly then moves along the shaft with respect to the fixed coils. The magnet is constrained on each end by a bracket which holds the shaft and a rubber bumper in addition to a light spring which provides a small centering force to the proof mass. A linear accelerometer is mounted in line with the shaft. A Linear Variable Displacement Transducer (LVDT) is utilized to measure the position of the proof mass with respect to the LMED assembly.

MAST TEST ARTICLE

The basic test article is a spare Voyager ASTROMAST built by Astro Research, Inc. It was supplied to MSFC by the Jet Propulsion Laboratory (JPL). The ASTROMAST is extremely lightweight (about 5 lb) and approximately 45 ft in length. It is constructed almost entirely of S-Glass. It was the flight backup Voyager magnetometer boom.

The ASTROMAST is a deployable symmetric beam which is triangular in cross section. Three continuous longerons form the corners of the beam and extend along its full length. The cross members, which give the beam its shape, divide the beam into 91 sections having equal length and mass and similar elastic properties. When fully deployed, the ASTROMAST exhibits a longitudinal twist of approximately 260 deg.

The test article can be reconfigured from this basic form to any of several different configurations such as the Cruciform configuration, the VCOSS-II configuration, and the ACES configuration. These configurations are described in the following sections.

STRUCTURAL TEST ARTICLE – ACES CONFIGURATION

There have been a number of structural test configurations evaluated in the MSFC LSS GTF over the past several years. Currently the facility is being utilized to evaluate the considerable national effort which was amassed by DARPA to study the active control of Large Space Structures. The "Active Control of Space Structures" (ACOSS) was begun in 1978 and lasted through 1984. A number of unique control techniques were developed, the most prominent and enduring being "High Authority/Low Authority Control" (HAC/LAC) by Lockheed, "Model Error Sensitivity Suppression" (MESS) by General Dynamics, and "Positivity" by TRW. The SDIO and AFWL determined that it would capitalize on the Government's investment by investigating at least these three techniques by implementing them on suitable hardware. The NASA/MSFC LSS Ground Test Facility was investigated and found to be suitable. AFWAL was selected to implement such a program, entitled ACES (Active Control Technique Evaluation for Spacecraft).

The ACES program was officially begun with a "Kickoff Meeting" at NASA/MSFC on 28 May 1986. It was attended by representatives from AFWL, AFWAL, NASA Langley Research Center, NASA MSFC, Aerospace Corporation, and Control Dynamics Company.

The LSS GTF configuration selected for implementing the ACES Program is a modified version of the Offset Antenna configuration. This is shown schematically in Figure 2.

The program began with the development of an analytical dynamic model. Concurrently, modal dynamic tests were performed. The conduct of the remainder of the program is primarily to implement the three controls techniques into the LSS GTF software and then test and assess their vibration suppression effectiveness. It is too early in the program to obtain results. The basic program is scheduled to be completed in October 1987.

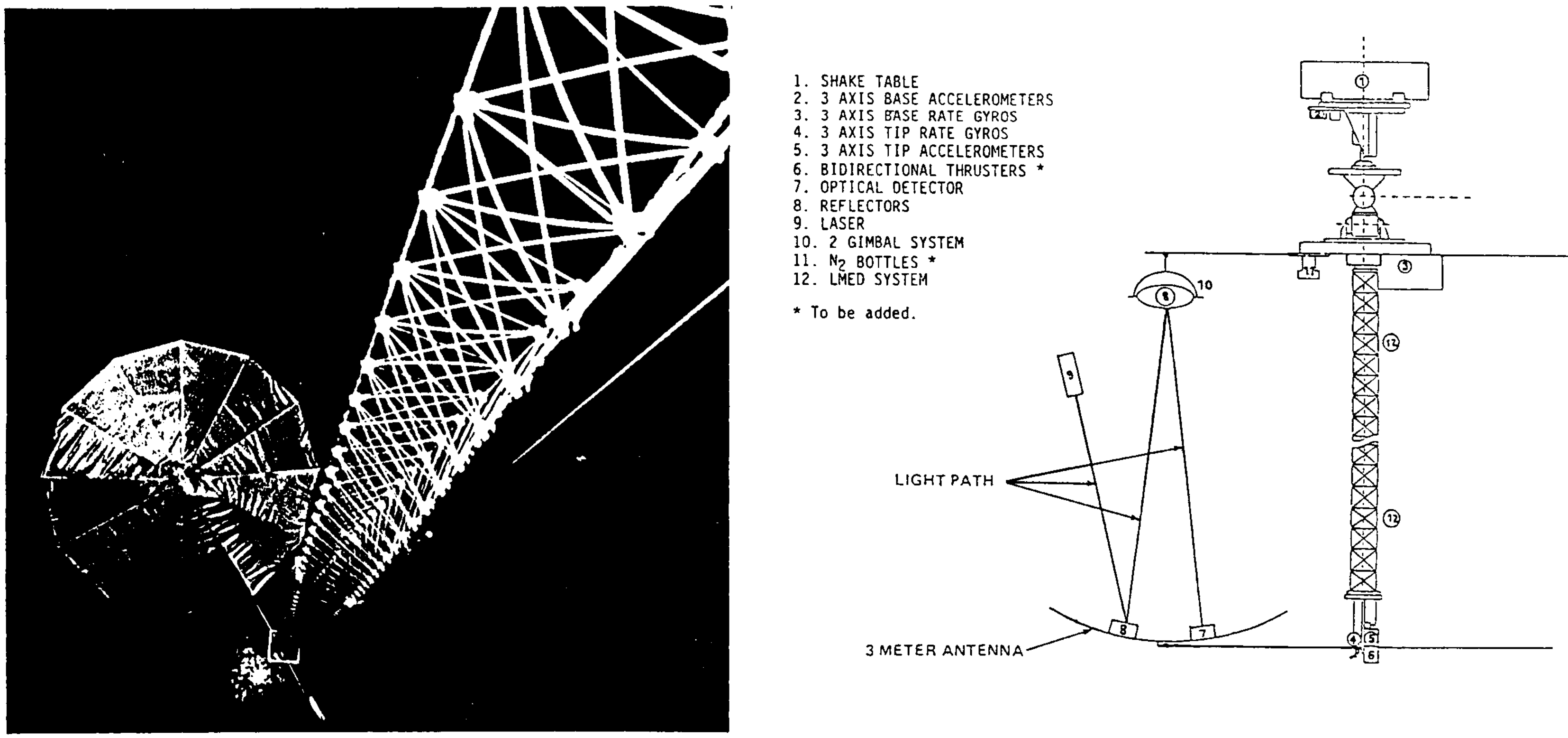

Figure 2. ACES configuration.

REVIEW OF TESTING/SIMULATION FACILITY PROBLEMS AND SOLUTIONS

The main purpose of this report is to describe the process of developing the GTF in such a manner as to be beneficial to similar travelers along this path. As such we will discuss a number of "blind alleys" that we went to along the way and will also illuminate some areas that may be strictly configuration dependent. But we believe and hope that our journey will be similar enough to interested readers so as to provide some grist for your mill as you proceed in your work.

The MSFC LSS GTF was envisioned from the outset to be a laboratory where control algorithms developed in the pure and well defined analytical world could be evaluated and honed in the real world environment in which they all must ultimately live and thrive. This original concept has been carried forward to the present time as the hardware and capability has grown. However, the learning process of dealing with real world hardware is not limited to just the testing of candidate control algorithms. Many issues and problems were faced and dealt with on a continuous basis. These issues were/are handled on an orderly and systematic basis through the joint cooperative effort of a number of disciplines and organizations. The active participation of a number of technical specialists from the outset is considered a prime driver in the success of the MSFC LSS GTF program. Such discipline areas are as follows:

- Modal test design and analysis
- Controls analysis and design
- Electronics
- Computer systems and programming
- Fabrication
- Sensors and actuators
- Simulation
- Program management.

Regularly scheduled meetings were/are held, minutes taken, and actions assigned. As a result surprises were minimized and problems anticipated. However, not all!

GENERAL PROBLEMS OF TESTING IN "1 G"

The GTF facility was first envisioned with the AGS facility rigidly mounted to the floor with the ASTROMAST extending vertically above. The weight of the ASTROMAST, tip instrumentation and structural weight was to be supported by an overhead tripod. This tripod was to be connected to the mast through a constant tension cable. The tripod itself was to be supported on three airbearing pads. However, it became quickly apparent that there were too many problems making this system work within cost and schedule constraints. The decision was made to solve these problems by inverting the whole system and to suspend the AGS from beams high in the building. This did away with the requirement to carry the load vertically but our problems with gravity field had just begun.

Of course we had to take care of such mundane considerations as the effects of the earth's rotation on the sensed accelerations and angular rates through the development and implementation of strapdown algorithms. But also each added element required that due consideration be given to the location of the center of gravity of the entire system. AGS torque capability and Astromast bending capability required that the center of mass be directly under the AGS gimbal system. Thus, as systems were added, such as the rate gyro package, additional balancing weights had to also be added to compensate and keep the center of mass under control. While these added weights did move the center of mass properly, this correction did not come for free. The roll moment of inertia and total system weight both went up. The added weight was a continuing problem due to the limited axial load capability of the ASTROMAST. In addition, as additional weight was added the mast tended to "unravel" and exhibit a corresponding change in the effective bending stiffness.

We learned that even after one had attached and balanced the required sensors and actuators to the structure that the problems of gravity were not over. How do you transfer information and power from and to the sensors, actuators and instrumentation when the structure is very light and flexible. The connecting cables not only add to the structural mass and stiffness of the structure but add a significant amount of damping to the system. This damping, while beneficial from a stability standpoint, does not present a true picture to the control system and thus gives the control designer too easy a job. We minimized the effects of cabling through elaborate suspension systems carefully designed through the "cut and try" method.

But gravity is not through yet. One of the lowest modes of the system turned out to be a "pendulum" mode of the configuration. This mode is not a structural mode at all and exists only because of the fact that the experiment is carried out in a gravity field suspended vertically. There is nothing that can be done about this mode but to recognize that it exists and to handle it in the control systems design and analysis. This mode had a frequency of approximately 0.14 Hz and would sometimes interfere with the conduct of successive tests – especially transfer function tests. These low frequency modes must be allowed to die out completely before initiating the next tests. The time constants of these modes are very substantial (10 to 15 min) and thus result in a lot of lost time as the test engineers wait around to start the next test.

DEVELOPING LSS PATHOLOGIES

Of course any self respecting structural analyst and test designer must give proper consideration and time to the well known demons – Large Space Structures PATHOLOGIES. What are these effects? Well, anyone can tell you that they are the three headed monster of

- Low structural frequency
- Low structural damping
- Closely spaced modes.

But how real are these effects? Do they really exist in real structures and if they do exist are they important. We found it extremely difficult to produce these effects in the facility. Equal beams were added in a cruciform manner to produce theoretical modes with similar closely packed frequencies but these were difficult if not impossible to excite and observe experimentally.

REAL WORLD STRUCTURAL BEHAVIOR

But closely spaced modes aside, we had an abundance of real world structural problems in the facility with which to deal and with which the control system analysts must cope.

Gravity reared its head again here. Beams which were assumed to be straight were bent under the load of gravity. Additional stiffness was added to vertical members due to the gravity restoring forces acting on the system. In addition, as the ASTROMAST "unwound" due to additional load being added, members which were assumed to be in tension only went completely slack. However, as the structure vibrated through large amplitudes, these members could pick up their tension and we would get the effects of a nonlinear stiffness.

We attempted to model these gravity induced structural characteristics as accurately as possible. The effects of gravity were included as geometric stiffness terms and the curvature of the arms was modeled by adding additional nodes to the structure to approximate the deviation from the straight line zero gravity conditions.

As mentioned earlier the theoretical model exhibited a higher modal density than we could observe in the actual structure. In addition, the torsional modes of the system were very difficult to excite and measure during the modal testing. We had to move the force exciters to point of high torsional modal gain. Modal testing of such a complex structure turned out to be a time consuming task. The number of accelerometers utilized to determine mode shapes was approximately 110. Several bandwidths (0 to 2 Hz, 1 to 3 Hz, and 4 to 8 Hz) were utilized by the structural analyzer in order to calculate the modes. Many averages (on the order of 100) were used to complete the mode shapes. Excitation was applied at two points simultaneously. The comparison between theoretical modal frequencies and measured modal frequencies in the test are summarized in Table 2.

TABLE 2. COMPARISON OF MODEL AND EXPERIMENTAL FREQUENCIES

Model Frequency (Hz)	Experimental Frequency (Hz)	Percent Error	Description
0.07	0.03	-133	Torsion
0.14	0.14	0	X-Bending
0.14	0.14	0	Y-Bending
0.53	0.637	17	Y-Bending
0.59			X + Antenna
0.59			Y + Antenna
0.60			Torsion + Antenna
0.70			X + Legs + Antenna
0.71			X + Legs + Antenna
0.73	0.752	3	X + Antenna + Arms
0.95			Antenna
0.95			Antenna
0.95	0.826	-15	Y + Legs + Antenna
1.00	1.042	4	X + Legs + Antenna + Arms
1.20	1.405	15	Torsion + Arms
1.34			Arms
	1.357		Legs
	1.466		Antenna Torsion
1.70	1.702	0	X + Y + Legs
1.73	1.752	1	X + Y + Legs + Arms
1.84			Y + Legs + Antenna
1.92			Antenna
1.92			Antenna
2.12	1.920	-10	Y + Antenna
2.20	2.000	-10	X + Arms
2.53	2.356	-7	X + Legs + Antenna
2.55	2.494	-2	Y + Antenna + Arms
3.31			Antenna
3.31			Antenna
3.80			Torsion
4.29	4.196	-2	X + Legs + Antenna
4.71			Antenna
4.71			Antenna
5.35			Antenna
5.45			Y + Legs + Antenna
6.73			Y + Z + Legs
6.87	7.023	2	Torsion + Arms
6.97	7.261	4	Torsion

In addition to normal modal testing, we performed a comprehensive series of control system related transfer function tests. There existed many actuator/sensor pairs for which transfer functions could be generated. The actuators include three gimbals and four LMEDs. The sensors include ten accelerometers located at the tip, base, and at each of the LMED locations, and six rate gyros located at the tip and base. Thus, there are 91 possible transfer functions for this configuration.

Of the possible input signals including random noises, impulses, pulses, sine sweeps or a specified time domain sequence, we selected a pulse. A pulse of 5*T was chosen, where T = sample period. This was the maximum length pulse that could be used which did not interfere with the determination of the transfer function. The pulse-length must be short enough so that the first zero of its frequency response is greater than the analyzer bandwidth. The pulse amplitude was determined to be the maximum for each transfer function without saturating the sensors. Ten averages were chosen through observation of the transfer function as different numbers of averages were used. Ten seemed optimal in the sense of minimizing the time required for each transfer function while maximizing the coherence.

We selected an analyzer bandwidth of 8 Hz based on

1. Being large enough to accommodate all significant modes in the theoretical model.

2. Minimizing the frequency intervals at which the transfer function is computed.

3. Corresponding to a sampling time which is close to the sampling time of the to-be-controlled system.

The vibration data was windowed to ensure that the response decayed to zero as required. The analyzer had a response time requirement of 32 sec which was not nearly sufficient for the low frequency modes of the system. Thus, a window of $\exp(-\alpha^* t)$ was utilized where $\alpha = 0.08312$. This α corresponded to forcing the signal to die out in 32 sec.

PESKY PROBLEMS

A number of pesky problems occurred throughout the duration of the test and some continue to this day. These problems are typical of that found in any testing program. We have included a partial list in Table 3 of a general nature and in Table 4 LMED problems. Of course this is not an exhaustive list but it is hoped that the inclusion of these will be of value to others in this field.

TABLE 3. GENERAL PROBLEMS

1. The antenna covering added substantial amounts of damping to structure. Solution: Remove the antenna cover from the test configuration. 2. The cables from the tip sensor package and the LMED packages to the computer system interfered with the structure through added damping. Solution: The attachment of the cables is done carefully and augmented with support ropes to minimize the interference with the structure. 3. The demand for faster computational capability increased throughout the test program and continues to increase. In addition, the computer system must be capable of accommodating higher levels of control algorithms. Solution: The computer system is being updated as follows. a. Assembly language COSMEC system. b. Basic language COSMEC system. c. Basic language COSMEC/HP 9000 system. The next step in the development of the computer system is a COSMEC/HP 9000/ Analogic vector processor system using FORTRAN.

FUTURE ACTIVITIES

The area of hardware verification for LSS control methodologies represents an unexplored region with vast potential. Several endeavors into the field have been undertaken as presented in the earlier sections of this paper. Other areas which represent enhancements to the existing MSFC facility are:

1) Unobtrusive Sensors and Effectors (USE)

2) Multiple Payload Pointing Mount (MPPM).

TABLE 4. LMED SPECIFIC PROBLEMS

1. The LMED initially exhibited very nonlinear behavior due to significant amounts of stiction.

   Solution: Many types of bearing shaft combinations were tried, and a very smooth matched bearing/shaft set was developed.

2. Large amounts of hysteresis were present in the LMED response.

   Solution: A non-magnetic aluminum bearing/shaft set was designed, developed, and fabricated.

3. Dynamic testing of the LMEDs, accelerometers and LVDTs was performed to verify the specified scale factors and voltage ranges. This testing was only done initially on one of the LMED packages which verified the manufacturer's specifications. The second LMED package was not tested but its actual performance turned out to be markedly different than the tested package.

   Solution: When the reworked LMEDs were available, the testing was performed on both packages to determine performance, scale factors, and voltage ranges for both packages.

4. The dragging of the LVDT core added significant amounts of damping to the LVDT. In addition, the LVDTs were not centered.

   Solution: The LVDTs must be "tweeked" so that the core does not drag. Also each LVDT must be adjusted so that the voltage range is as symmetrical as possible.

Unobtrusive Sensors and Effectors

Currently, most control hardware used for LSS vibration suppression consists of lumped mass elements which, through their distribution on the LSS article, change its structural characteristics. The development of unobtrusive sensors and effectors would assuage this problem. Several viable candidates have been suggested, including the use of piezoelectric polymers. The piezo material could be used either as a sensor or an effector or both. Other possible alternatives include the use of fiber optics as distributed sensors as well as remote sensing techniques such as optical reflectors. Plans are underway to enhance the present facility to allow for the introduction of unobtrusive sensors and effectors technology.

Multiple Payload Pointing Mount (MPPM)

A challenging control problem associated with the LSS field is that of multiple payload pointing. The Advanced Solar Observatory (ASO) is an example of this situation in which at least two pointing mounts will be operated independently of one another while secured to a flexible structure. Little work has been ventured in the problems associated with the MPPM experiment.

To address the MPPM problem, MSFC plans to erect, in its LSS ground test facility, an experiment situation similar to the ASO (Fig. 3). The first phase of this plan will be the construction of the air bearing table (which will allow translation in a plane and rotation perpendicular to that plane) and the pointing mount for the Pinhole/Occulter Facility (P/OF) experiment. The P/OF will consist of a three-axis gimbal system with its payload mounting plate on which will be located an inertial reference unit and the SAFE-I boom. The SAFE-I boom will have an end plate similar to that of the P/OF. The total structure configuration will be "tuned" so that it possesses similar structural characteristics of the POF. After "tuning" this structure, a dynamics and control verification will be effected so that any possible "surprises" can be studied and eliminated before the POF flight.

SUMMARY AND CONCLUSIONS

Our development work has been a learning experience for not only the control system engineers participating in the effort but the entire team as well. We have had reinforced in our engineering intellect the harsh realities of having to deal with real structures and systems that cannot be forced to stay in a neat analytical box. The eventual testing of control methodologies that have been developed over the past several years in this "real world" environment is sure to drive out any weaknesses that may exist and allow the truly "robust" control system techniques to emerge from the pack.

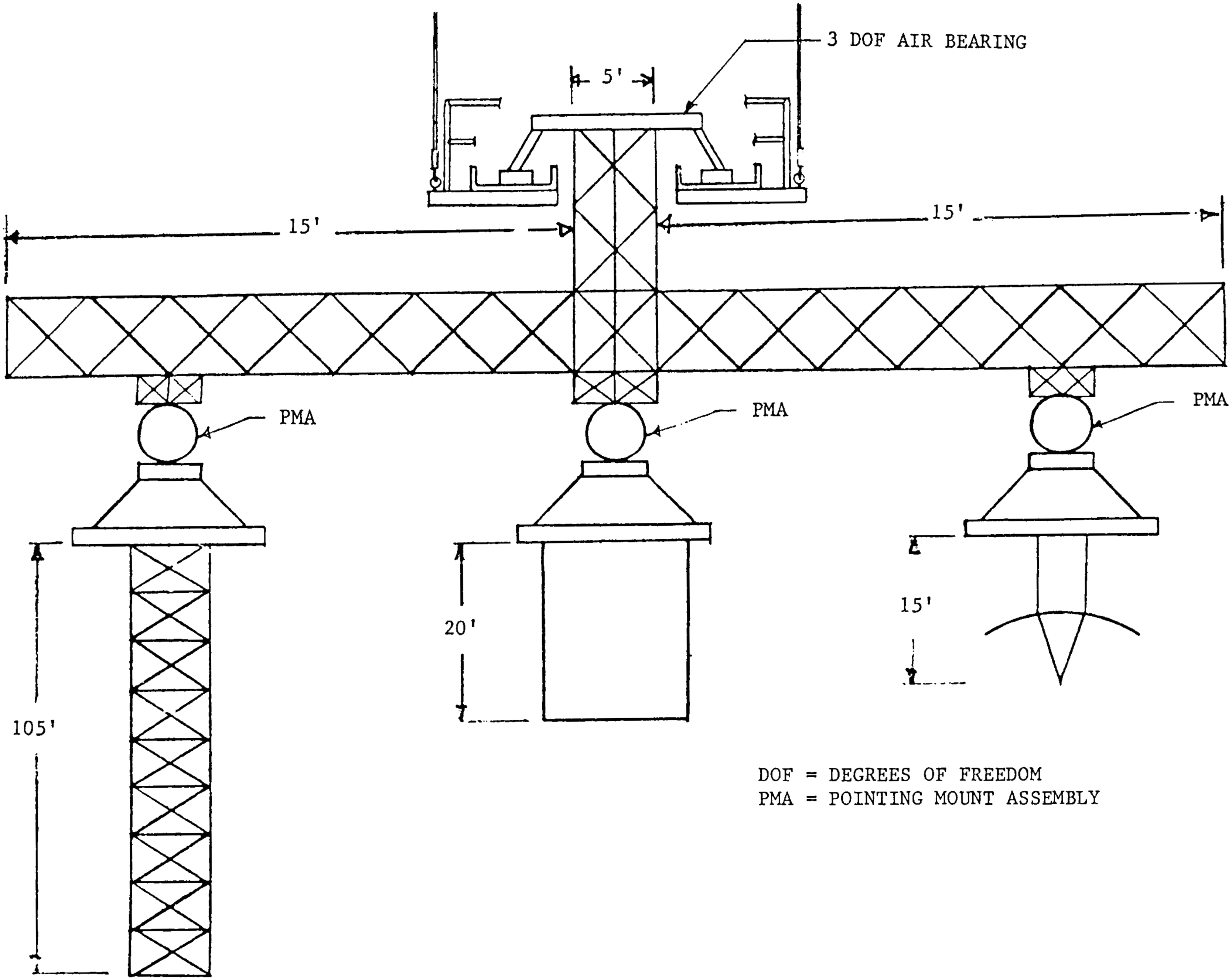

Figure 3. MPPM configuration.

APPROVAL

LARGE SPACE STRUCTURES TESTING

By Dr. Henry Waites and Dr. H. Eugene Worley

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

G. F. McDONOUGH
Director, Structures and Dynamics Laboratory

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